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A model for the planning of maneuver unit and engineer asset placement

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THESIS

A MODEL FOR THE PLANNING OF MANEUVER UNIT

AND ENGINEER ASSET PLACEMENT

by

Dean E. Craig

September 1985

Thesis Advisor S.H. Parry

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A Model for the Planning of Maneuver Unit and Engineer Asset Placement

by

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Submitted in partial fulfillment of the requirements for the degree of

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September 1985

ABSTRACT

This thesis develops a prototypical model for the planning of maneuver unit and engineer obstacle placement for the Airland Research Model under development at the Naval Postgraduate School. The model utilizes a multidimensional network for the representation of terrain and presents two algorithms for combat planning. A mid-European scenario for a brigade in defense is used to contrast the model solution to combat planning problems with established tactical doctrine. The prototypical model demonstrates that network methodologies provide an efficient means for terrain representation in large scale combat modeling.

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I. INTRODUCTION

A. THE AIRLAND RESEARCH MODEL

The Airland Research Model is an area of continuing research at the Naval Postgraduate School. This modeling effort attempts to simulate the complex integration of ground maneuver forces, fire support weapons, and Army and Air Force aviation assets of the U.S. Army's Airland Battle doctrine. The focus of this model is at corps and division level operations. The Airland Battle doctrine calls for defeating the enemy by stopping their forward elements, by destroying their second echelon before its combat power can influence the battle, and by interdicting the lines of communication and resources needed to support the forward elements. This thesis continues the research effort by exploring methodologies for simulating the combat planning process at the battalion task force level.

The research to date [Ref. 1:pp. 1-3] has focused on the development of a model which will operate without human intervention to produce audit trails of cause and effect relationships. To operate in a systemic mode, modules must be developed to simulate both planning and implementation of operations at corps level and each of the subordinate levels of command. Individual research to date has dealt primarily with the planning modules for the varying levels of command within the corps. From this initial research, it was apparent that as the level of command planning moves down from corps to battalion, the information necessary for planning must increase in resolution. Furthermore, the value of the elements of combat will vary with respect to the area of influence of the level of command. As a result, previously used methods of representing terrain, transportation systems, communication links, fixed combat assets, and mobile combat assets were no longer feasible. Therefore, as an initial approach, it was decided that the network disciplines would be used to provide the structure for representation of these elements. This would further provide a capability to investigate several model building methodology alternatives such as variable resolution, aggregation, and distributive processing.

To achieve this systemic model, a set of rule-based systems is being developed to represent the command and control processes of the Airland Battle doctrine. These systems must then be converted to algorithms by which the model simulates the decision processes within the corps. These algorithms would simulate decisions such as deployment of forces, task organization of combat maneuver units for battle, and allocation of support elements (indirect fire, air, engineer, and logistical) [Ref. 1: p. 2]. With the exception of the Soviet troop control module, the development of planning modules has resulted in only suggested theoretic approaches for the simulation of battalion and brigade operational planning.

As a major departure from past modeling methodologies, the use of network structures is being explored as a more efficient way of representing battlefield terrain. Past methods such as the use of hex terrain, digitized terrain, or functional terrain are very expensive in terms of data storage requirements and computational time. These types of structures also fix the level of resolution to a specific scale. Typically hex terrain for a corps level model encloses several square kilometers within the boundaries of a hexagon. These boundaries are then coded with attributes which represent an aggregation of the terrain within the hexagon. Digitized terrain can represent features in very high resolution, but neither method provides a means to vary resolution in the model.

As early as the mid 1960's network formulations were being used to represent lines of communication such as road systems or rail systems in enemy rear areas. These models were used by the Air Force for planning of bombing strategies. The models typically defined arcs with one dimension such as length or capacity. Later models began to attribute more dimensions to arcs such as length, capacity, and length of time required to repair the arc if interdicted. A similar use of multidimensional nodes and arcs to represent terrain has been proposed for the Airland Research model. In this multidimensional terrain network, the nodes of the network represent physical locations on the ground such as cities, road junctions, and hilltops. Arcs represent feasible routes of movement from one location (node) to another. A major effort in the Airland Battle model was the development of a theoretical approach for the network representation of terrain, communications links, logistical systems, and command structures.

To accommmodate the changing values of the elements of combat, a hierarchical architecture has been proposed for the model. Figure 1.1 shows a schematic representation of the areas of influence in space and time for the levels of command within a corps. At the corps level of command, planning horizons typically are concerned with activities which may occur 24 to 72 hours into the future and extend as far as 300 kilometers into the enemy rear area. At the battalion level of command, planning horizons are concerned with activities which may occur 1 to 6 hours into the future and extend 15 kilometers into the enemy rear area.

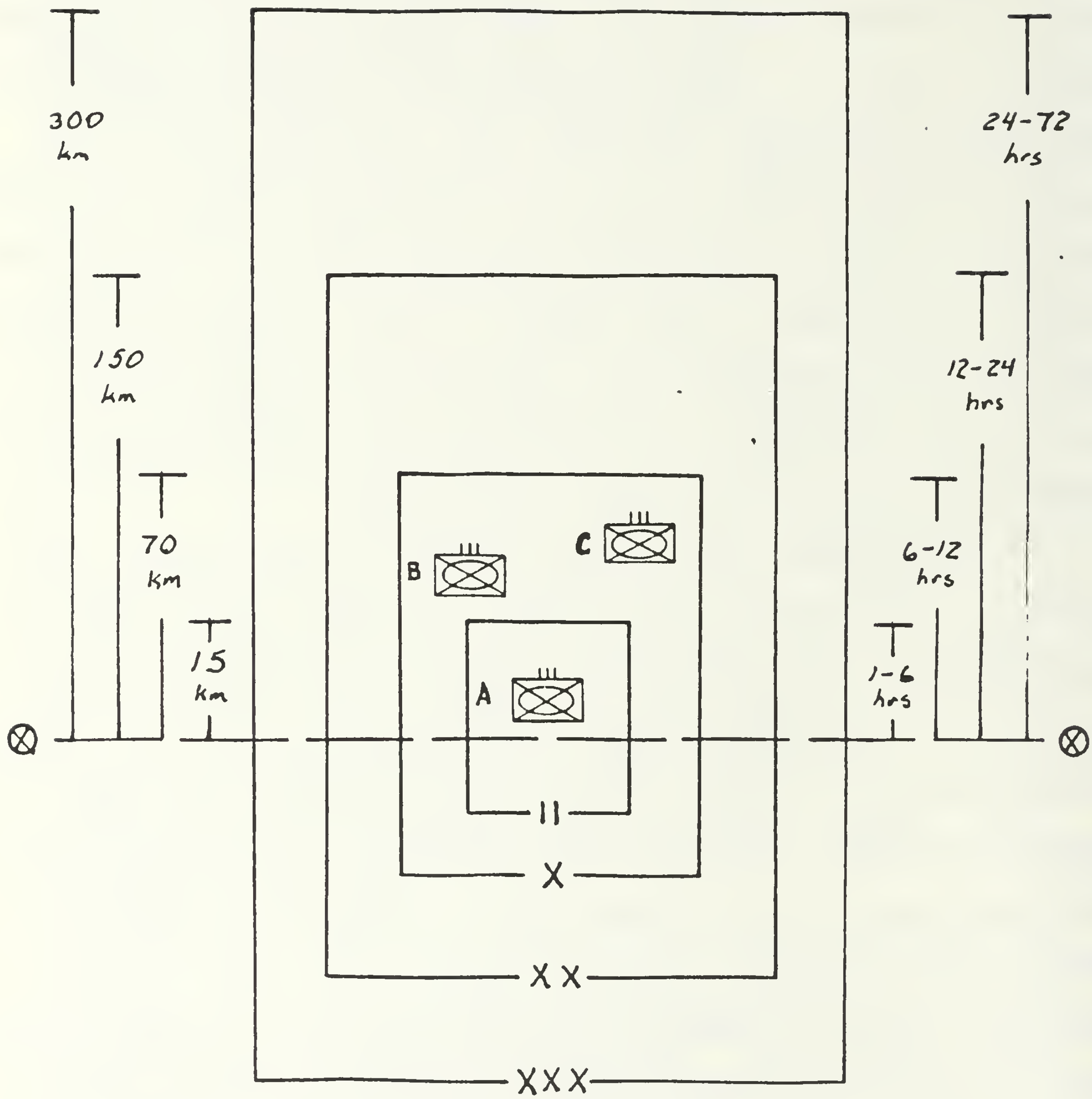

Figure 1.1
Areas Of Influence Within a Corps

Therefore, the battalion depicted is typically concerned with the activities of motorized rifle regiment (MRR) A. The combat potential of this MRR has great value in determining the battalion's courses of action. The other two MRR's, B and C, though they may have the same combat strength, do not have the same value in the battalion's planning because they are out of the battalion's space-time area of influence. The brigade in the figure is concerned with the activities of all three MRR's. Each individual MRR has less value in the brigade planning then it does to the battalion, but the value of the three MRR's together is not just the sum of their individual values. The three MRR's which make up a motorized rifle division (MRD) have a value which is dependent upon it relation to the brigade in space and time. To facilitate this varying value of combat elements, a Generalize Value System (GVS) is being developed for the model [Ref. 2]. Again the use of hex or digitized terrain methodologies would make the determination of the space and time relationships required of the GVS very cumbersome. On the other hand, the allocation of assets such as minefields, artillery, or aviation, and their current and future values to different levels of command, can easily be treated as arc or node characteristics.

B. PURPOSE AND GOALS

The Airland Battle model is a research model being developed at the Naval Postgraduate School (NPS). As a result, each student's work builds upon the work of previous students, providing validation of previous efforts, new concepts, new methodologies, and recommendations for areas for further research. The total effort is directed toward the ultimate goal of producing a working model of the Airland Battle concept.

In previous work on the Airland Battle model, a great deal of effort has been expended in the development of approaches for the simulation of combat planning. Two theses by Boyd [Ref. 3] and Kazimer [Ref. 4] proposed algorithms for the simulation of the planning for the allocation of brigade engineer assets and the deployment of the combat units of a battalion task force. These algorithms suggest that decisions for these allocation problems can be represented as a process of locating the minimum time path through a transshipment network and then interdicting the path by allocation of assets on its arcs. In addition, a thesis by Krupenevich [Ref. 5] describes the characteristics of the Airland Battle transportation network, represented as node and arc "attributes." These works have presented theoretical approaches, and as yet, a working model has not been developed which integrates these concepts and tests the validity of the algorithms.

Therefore, the purpose of this research is to develop a working model for planning the placement of engineer assets and combat units at battalion level, and to demonstrate the applicability of network formulations of terrain to large-scale combat modeling. The decision logic for placement will be based on a shortest time path finding algorithm to test the validity of the heuristic approaches to engineer and combat maneuver unit allocation proposed in work by former NPS students. The model will utilize a network formulation of the terrain within a corps maneuver area. This is the first effort to actually develop a working network representation of terrain for the Airland Battle model. Therefore, the primary importance of the research is to determine the applicability of this network methodology. This is to be done by determining if the model fails to achieve reasonable results. If a failure occurs then it will be analyzed to ascertain if the failure is due to errors in the formulation of the network or algorithms, or if the methodology itself is at fault. Furthermore, if the methodology is sound, these failures will provide the directions for further research.

C. METHODOLOGY

Since this is a prototype model and implementation, ease of programming was the primary factor affecting selection of a programming environment. The model is designed to run on an IBM PC. A micro-computer was selected because the limited memory and data storage increases the necessity for using efficient data structures and algorithms. PASCAL was selected as the programming language because it provides for data structures that are very compatible with network data structures. It also allows for large variable names which provide easy internal program documentation. The model was written using a TURBO PASCAL compiler because of its speed.

In order to define the physical boundaries of the network and to ascertain the validity of the algorithms, a combat scenario within which to frame the problem was selected from the U.S. Army Command and General Staff College (C&GS) literature. This scenario not only limits the scope of the problem, but also provides a "school approved solution" to the engineer and combat unit allocation problem with which to compare the model results. This scenario and its effect on the problem constraints will be discussed in Chapter II. In Chapter III, the two previously proposed algorithms for the planning of combat unit placement and engineer asset allocation and placement will be reviewed. The network formulation and its associated data structures will then be presented. Chapters IV and V will describe the algorithms for combat unit placement and engineer asset allocation in further detail. They will present the modifications required to implement these algorithms using network data structures, and will compare the model results with the C&GS solution. Suggestions will be made as to possible further modifications to the network and the algorithms where spurious results occur. Chapter IV will summarize the results of the research and provide suggestions for other possible applications of the transportation network in combat planning.

II. SCENARIO

To provide a framework for the development of the network and the validation of the results of the allocation algorithms, a battle scenario was selected from the U.S. Army C&GS literature. In the combat planning process, the corps analyzes the terrain within the corps sector for likely avenues of approach. These avenues of approach for corps planning represent terrain that will allow the movement of enemy division sized units. Based on these likely avenues of approach the corps allocates maneuver forces to achieve friendly to enemy combat force ratios of 1 to 3 in the main battle area. Depending on the size of the friendly force assigned to the avenues of approach, one or several avenues will be assigned to subordinate division headquarters. Lateral boundaries are then defined between the avenues of neighboring divisions. For a further discussion of this process see [Ref. 6:pp. 6.5-6.32]. This process continues with the division assigning boundaries for maneuver brigades and brigades for battalions. At the battalion level specific positions on the ground are assigned to company task forces.

Along with the planning of boundaries which define the sector of operation for the subordinate units, an overall scheme of maneuver is developed. From this scheme subordinate units are given missions to accomplish in their assigned sector such as defend , delay or attack. Higher headquarters will allocate assets for engineer obstacles, artillery fire, and air support to enhance the maneuver scheme. Thus, a subordinate may be assigned a sector which has already been modified with obstacles and supported by air and artillery assets. These assets must then be incorporated into their scheme of maneuver. The assumption is made that the model will have the capability to pass such a scenario in some parametric form to the planning modules for each unit subordinate to the corps level. The planning modules for these subordinate units will develop courses of action to achieve their specified mission, and then in turn, pass scenarios to their subordinate units. This continues down the chain of command to the lowest level of the model's resolution. For planning the allocation of engineer assets and maneuver units, this lowest level is battalion level.

The battalion planning module must position battalion level engineer assets and company combat task force units at specific locations on the network to achieve the battalion's combat mission. Therefore, a scenario was selected which specifies a brigade's mission, task organization, and area of operation. Within this framework, a battalion scenario was developed and the parameters passed to the battalion planning module. This will allow for a large enough scope of operations to require both the planning of engineer assets allocation and company task force allocation, which is done at battalion level.

A. BRIGADE SCENARIO

The scenario selected for the brigade is a "defend in sector." The sector is located along the East and West German border just north of Fulda [Ref.6: pp. 6.14-8.29].

1. Brigade Situation

The brigade's sector has lateral boundaries extending three to four kilometers forward of the Forward Line of Troops (FLOT) with the general trace north to south along autobahn (NB412328) to road junction (NB379281) to Hatterode (NB358231) to brigade lateral boundary (NB360200). The 2nd Brigade, 23rd Armored Division (defender force) has received the mission to conduct an active defense in sector. The brigade is to establish a covering force on D-Day, H-Hour and defend in sector. The covering force is to be established along the international border from (NB495348) to (NB408220). The 2nd brigade defends in sector from (NB495348) to (NB408220) and prepares battle positions. The 2nd brigade has been assigned six combat maneuver battalions (three tank battalions, two mechanized infantry battalions, and one armored cavalry squadron), an engineer task force of six companies, and elements of a Combat Electronic Warfare Intelligence (CWEI) battalion. In addition, an artillery battalion has been placed in direct support of the brigade. The 2nd Brigade task organization is shown in Table I. Friendly forces are to the left, 1st Brigade, 23 Armored Division, and to the right, 3rd Brigade, 23 Armored Division. The brigade is opposed by a motorized rifle division (attacker force).

TABLE I

2ND BRIGADE TASK ORGANIZATION

1-92 Mech	Task Force 510
1-93 Mech	510th Engr Cbt BN (Corps) (-)
1-10 Armor	B/23rd Engr (OPCON)
1-12 Armor	D/23rd Engr (OPCON) (-)
1-14 Armor	2/B/23d CEWI
1/201st Armd Cav Regt	1 OPSEC Tm/23d CEWI
1-51 FA(DS)	1 IPW Tm/23d CEWI
2/A/1-440 ADA	

Because the brigade is opposed by a motorized rifle division, it is reasonable to assume the attacker force will deploy with two motorized rifle regiments forward (the "first echelon attack force") followed by a reinforced tank regiment (the "second echelon attack force"). The concept of the sector defense will then require that the defender brigade covering force attack the leading forces of the attacker first echelon in the forward covering force area

(CFA), causing it to deploy into attack formations and inflicting as many casualties on this first echelon as possible. After the covering force battle is completed, the remaining 2nd Brigade battalion task forces will destroy the remainder of the first echelon forces in the main battle area (MBA). This will be done by concentrating the combat force of the battalion task forces at advantageous locations throughout the MBA, taking advantage of superior fire and maneuver. The Airland Battle doctrine would then require the use of air and artillery fire to be concentrated on the second echelon force, the attacker tank brigade, destroying its ability to press the first echelon attack, and interdicting supply lines that support both echelons.

2. Brigade Course of Action

To achieve its mission, the 2nd Brigade has developed the following course of action: the brigade will employ two combat battalion task forces in the CFA, a tank-heavy task force to the north, and an armored cavalry squadron to the south. The remaining three battalions will be deployed in the MBA as follows: Task Force 1-92 will be deployed in the northern sector defined by the brigade's northern sector boundary and a line from (NB435270) to (NB379285). Task Force 1-14 will be deployed in the center sector. Task Force 1-93 will be deployed in the south in a sector from the line Hatterode (NB358231) to (NB415240) to the brigade southern boundary. Two engineer companies will be deployed for direct support of the covering force units, and one engineer company for direct support of each battalion task force in the MBA. The remaining engineer company (-) will be held for support of the brigade rear area units.

B. BATTALION SCENARIO

Within this brigade scenario, a scenario is developed for one of the battalion task forces [Ref. 6:pp. 9.1-9.19]. In the sector defense, the battalion task force can defend alone or as part of a larger force. It attempts to defeat the enemy force using fire and maneuver to destroy substantial portions of the enemy force while attempting to minimize losses to its own force. This is as opposed to a strong point defense mission where the task force is to hold a specific position until told to move. By selecting terrain and using obstacles to its advantage, the enemy can be forced to slow its movement, and congestion can be created in the enemy battle formations. Thus the enemy's lines of fire are obstructed by its own forces and the task force can concentrate it fires for a longer time. The task force commander selects battle positions which allow weapons to engage the enemy at maximum range and which impede the advance of the enemy force allowing concentration of fire as long as possible on the slowed enemy force.

Task Force 1-14 has been assigned the mission of defending the center sector of the brigade. This sector is bounded to the north by the line from (NB435270) to (NB379285), and in the south by the line from Hatterode (NB358231) to (NB415240). Task Force 1-14 is task organized as shown in Table II.

TABLE II

TASK FORCE 1-14 TASK ORGANIZATION

- Team ALFA
- A/1-14 Armor(-)
  - 1/A/1-93 Mech
  - 1 Redeye Tm (DS)
- Team CHARLIE
  - C/1-14 Armor
  - 2/A/1-93 Mech
  - 1 Redeye Tm (DS)
  - 1 AVLB Tm (DS)
  - 1 GSR Tm (DS)
- Team Mech
  - A/1-93 Mech (-)
  - 1/A/1-14 Armor
  - 1 Redeye Tm (DS)
- B/1-14 Armor
- 1 Redeye Tm(DS)
- Cbt Spt Co (-)
  - Sct Plt
  - AVLB Sec (-)
  - 1 GSR Tm (DS)
- TF Con
  - Hvy Mort Plt
  - Redeye Sec (-)
  - B/510 Engr (DS)

The task force is opposed by a motorized rifle regiment. Figure 2.1 shows the maneuver area and boundaries for the 1-14th.

C. ASSUMPTIONS AND CONSTRAINTS

These scenarios allow several simplifying assumptions. The engineer and combat unit allocations are for Task Force 1-14, which has an MBA defend mission. Therefore, when

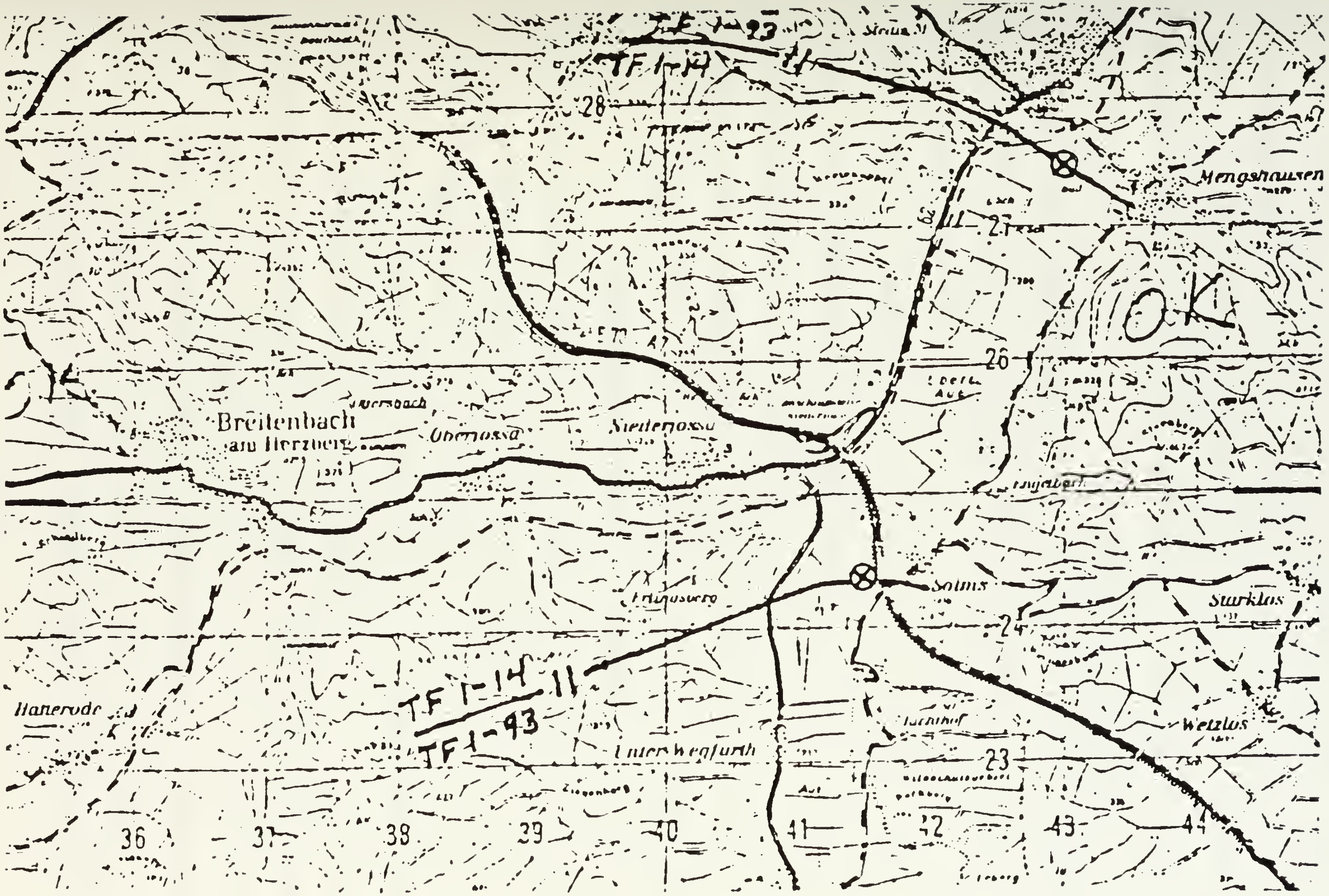

Figure 2.1
1-14th Maneuver Area

attacker forces arrive in their sector, they will have deployed into battle formations as a result of the covering force battle. Because the attacker force doctrine prescribes specific vehicle spacing in their deployed formations, many of the model parameters describing the attacker force can be treated as constants in the model.

Because the planning is to be conducted for the initial allocation of units and engineer assets, the amount of time required to implement the plan will be on the order of several days. Thus, time is not a critical factor, and feasible plans are not constrained by such factors as time available to arrive in battle positions or time required to prepare battle positions. Further enhancements which model decisions after initial engagement with the enemy will necessitate implementation of time constraints.

Having developed this scenario, the objective of this research can be described more explicitly in terms of a brigade and battalion operation plan. Algorithms must be developed which generate courses of action that simulate the brigade and battalion planning process. A network must be developed which adequately describes the terrain in brigade sector in terms of the algorithm variables. It must take into account the variables used in the decision process and represent these variables in the form of characteristics of the arcs and nodes of the network. Data structures must be selected which support efficient computer representation of the network and efficient operation of the algorithms. The results of the computer planning model must be tested to determine if the resultant plans reasonably represent the actual plans developed for this combat scenario. Finally, the spurious results must be analyzed to determine possible modifications to the network or algorithms to correct them.

III. ALGORITHMS AND NETWORK FORMULATION

A. BACKGROUND

The need for the Airland Research Model to operate in a closed mode requires the abandonment of past methods for the computer representation of terrain. The past methods of hex terrain, digitized terrain, and functional terrain are too inefficient in terms of data storage and computational time to facilitate the varing levels of detail needed to support the planning modules [Ref.5: pp. 14-15]. Over the last twenty years, a wealth of research has been conducted in the area of network methodologies. As a result, an extensive library of algorithms has been compiled which provide efficient techniques for determining paths and flows through networks. In many cases the rule-based systems of the Airland Research Model can be stated in terms of probable paths for units and flows of supplies through a battle maneuver area. Therefore, to capitalize on these new network technologies, it was decided that initial research on the Airland Research Model should be directed toward the use of network methodologies for the underlying data structures throughout the model. This is a departure from usual terrain representations, and is one of the major innovations of the Airland Research Model.

B. ALGORITHMS

To model planning processes in the closed architecture of the Airland Research Model, a rule-based system has been proposed. In this system, decision rule sets are developed from the Airland Battle doctrine. These rule sets are then implemented as algorithms to situations arising during the simulated actions taking place in the model. These algorithms then produce courses of action which represent the result of planning and decisions of commanders at different levels within the model.

In this thesis, two proposed alogrithms will be analyzed to determine their applicability in the Airland Research Model. The first of these algorithms, the "Unit Placement Algorithm," deals with the initial placement of the maneuver units of a battalion task force. The second algorithm, the "Engineer Asset Placement Algorithm," deals with the allocation and positioning of barriers and obstacles within the battalion task force maneuver area. Both of these algorithms handle the problem of interdicting the movement of an enemy force through the battalion maneuver area.

The rules upon which these two algorithms are based are derived from both U.S. doctrine and Soviet doctrine. U.S. Army doctrine dictates that defensive positions should be selected which take maximum advantage of terrain for cover/concealment, fire, and maneuver along the most likely enemy avenues of movement, referred to as avenues of approach. The initial unit positions should be close to the forward boundary of the assign sector to facilitate repositioning of forces in the sector after the initial engagement. The placement of engineer barriers and obstacles should support these unit battle positions throughout the sector to impede the movement of the enemy forward of the battle positions. To take maximum advantage of this impeded movement, the barriers and obstacles should be covered by direct and indirect fires. Based on Soviet doctrine, the most likely avenues of approach are paths through the sector which allow the fastest rate of movement to their objectives. Typically Soviet objectives are located deep behind the battalion sector's rear boundary.

From U.S. doctrine, the nature of the objective functions for both the Unit Placement and Engineer Asset Placement can be formulated. Consider a terrain network, G(V,E), where V represents the nodes and E the arcs of the network. The attacker force enters the network at the local supply node s, with an objective at terminal node t. The desired objective is to identify from the set of feasible placement plans { X }, the candidate plans { X^* }, which maximizes the minimum travel time from s to t of the attacker force. Furthermore, in the case of the unit placement problem, from the candidate plans { X^* }, select the plan $\hat{X}$ that minimizes the maximum distance from s to any units. As will be discussed in Chapter V, to achieve cover by fire for the barriers and obstacles, the addition of this second objective function is necessary for the Engineer Assets Placement Algorithm as well. The feasibility of a placement plan X is constrained by the assets available to be placed on the arcs of the network.

In the late 1960s and early 1970s, interdiction models were developed for the Air Force which solved an airstrike problem similar to the engineer problem. These models used small networks of five to twenty-five nodes and ten to several hundred arcs. Though the models achieved optimal solutions through the use of integer programming, the solution time for the larger of these problems took several minutes. [Ref. 7]. The requirement to solve these types of problems as many as fifty times just for the initial planning phase makes similar approaches infeasible. In a review of available solutions methods for interdiction type problems [Ref. 4: pp 83-84] for the Airland Research Model, it was concluded that to achieve reasonable solution times for the model, heuristic approaches must be developed to treat the problem.

The two proposed heuristic algorithms have several common features. A battalion sector must be identified from the larger maneuver area. A minimum path must be determined through battalion sector. A cost function must be developed for determining the minimum path which is a function of enemy unit, travel time based on the terrain characteristics of the path, delay forces allocated to the path, and obstacles allocated to the path.

1. Unit Placement Algorithm

The placement of company sized units within the battalion task force sector is determined by the following rule:

> For Delay Destroy mission, place the unit on the shortest time path (avenue of approach) through the battalion sector. The unit is to be located so maximum effective range of the unit's weapon system can be achieved. The site should be as far forward in the sector as possible under the above restriction.

Boyd [Ref. 3: pp 71-72] proposes a heuristic algorithm from this rule. It is assumed in this algorithm that the terrain network for the battalion sector is available as an input to the algorithm. In the implementation of this algorithm the first step is to determine the nodes and arcs of the total terrain network which lie within the boundaries of the battalion's assigned sector. The creation of the battalion sector network from the total network is discussed in Chapter IV. The algorithm follows:

Inputs: Battalion sector terrain network with supply node s and terminal node t, set of units and unit characteristics, mission definition.

Outputs: Set of arcs associated with the placement of each Unit.

Step 1. Determine the minimum time path for movement of the enemy through the network from s to t.

Step 2. Determine the specific mission of the friendly forces.

Step 3. Determine the maximum effective range of the primary weapon system of the unit for the site. Choose the site with the largest maximum effective range as the placement site. Ties are broken by selecting the site closest to the FLOT.

Step 4. Place the maneuver unit with the largest Standard Unit of Armorment (SUA) on the selected site. (SUA values will be discussed later)

Step 5. If all units have been positioned, Stop. Otherwise go to Step 1.

2. Engineer Assets Placement Algorithm

The rule for the allocation and positioning of engineer assets on the battlefield is similar to that of positioning combat units. The rule is:

> On the shortest time path (avenue of approach) through the battalion sector, place the type obstacle in the location which minimizes the use of engineer assets, and maximizes the time to traverse the resulting path.

From this rule Kazimer [Ref. 4: pp. 84] proposes the following algorithm. As with the Unit Placement Algorithm, the terrain network for the battalion sector is treated as an algorithm input.

Inputs: Battalion sector Terrain Network with source node u, sink node v,and arcs identified with target types; listing of interdiction methods identified with assets needed to perform the interdiction, enemy threat unit type t.

Outputs: Set of arcs to be interdicted identified with interdiction method.

Step 1. Initialize the data.

Step 2. Calculate the minimum time path of a type t enemy unit through the network from the source node u to the sink node v.

Step 3. Select and interdict the most cost effective, feasible target on the path from Step 2. If no selection can be made, terminate the algorithm.

Step 4. Return to Step 2.

In Step 3, the most cost effective interdiction method is defined as the method which has the largest ratio of delay time to assets required to perform the interdiction, where each type of asset is assigned a relative value.

It is one of the objectives of this thesis to determine if these common requirements can effectively be dealt with using network methodologies.

C. NETWORK FORMULATION

To support these algorithms a transshipment network was constructed. This network represents the 2nd Brigade sector. Though this is larger than necessary to test the algorithms on the 1-14th scenario, it will provide for further research into the brigade level maneuver and allocation modeling.

The network structure can exploit the mathematical nature of the variables of the decision process by representing these variables as characteristics of the arcs and nodes in the network. It is an objective in developing this network to adequately describe the terrain and combat effects on maneuverability necessary for the implementation of the two algorithms with a minimum number of characteristics for each arc and node.

1. Node Characteristics

In the network, nodes are used to represent actual terrain features. Four characteristics were used to describe a node: an integer node identification number, three digit latitudinal coordinate, three digit longitudinal coordinate, and type. This provides the information necessary for selecting the nodes which are located in the 1-14th's sector of the network. The coordinates were simple map grid coordinates. The type was entered as a single integer value. Table III shows the integer values and the terrain feature it represents.

TABLE III

TYPE VALUE AND CORRESPONDING TERRAIN FEATURE

Integer Value	Terrain Feature
1	City
2	Village
3	Autobahn Junction
4	Road Junction
5	Hill Top
6	Other

The primary function of the node in the transportation network is to relate the junction of arcs in the data representation to physical locations on the map. In addition, they represent possible objectives in a combat mission. Figure 3.1 shows the location of the nodes in the 1-14th's sector superimposed over a map of this sector.

2. Model Implementation of Node Characteristics

In the model, the node representations are developed through the use of two record types, NodeRec and PlotRec. These two records types are further consolidated into an array type called Nodes. A variable of type nodes, called Node, is then used in the program to store the node data.

The record type NodeRec contains a modification of the basic node representation discussed in III-C-1. An additional data item, called Start, is added. The item Start is used to store the address of an arc in the file of arcs so that the array Node may also be used as an entry point array.

The record type PlotRec contains data on each node that is required for implementing algorithms and graphic displays of the data. PlotRec expands the amount of information maintained on each node by providing for six additional data items to be associated with each node: Base, Horz, Vert, Section, Cost and Prev. The data item Base is of record type NodeRec and is used to store the basic node data in the expanded PlotRec record. The items Horz and Vert are

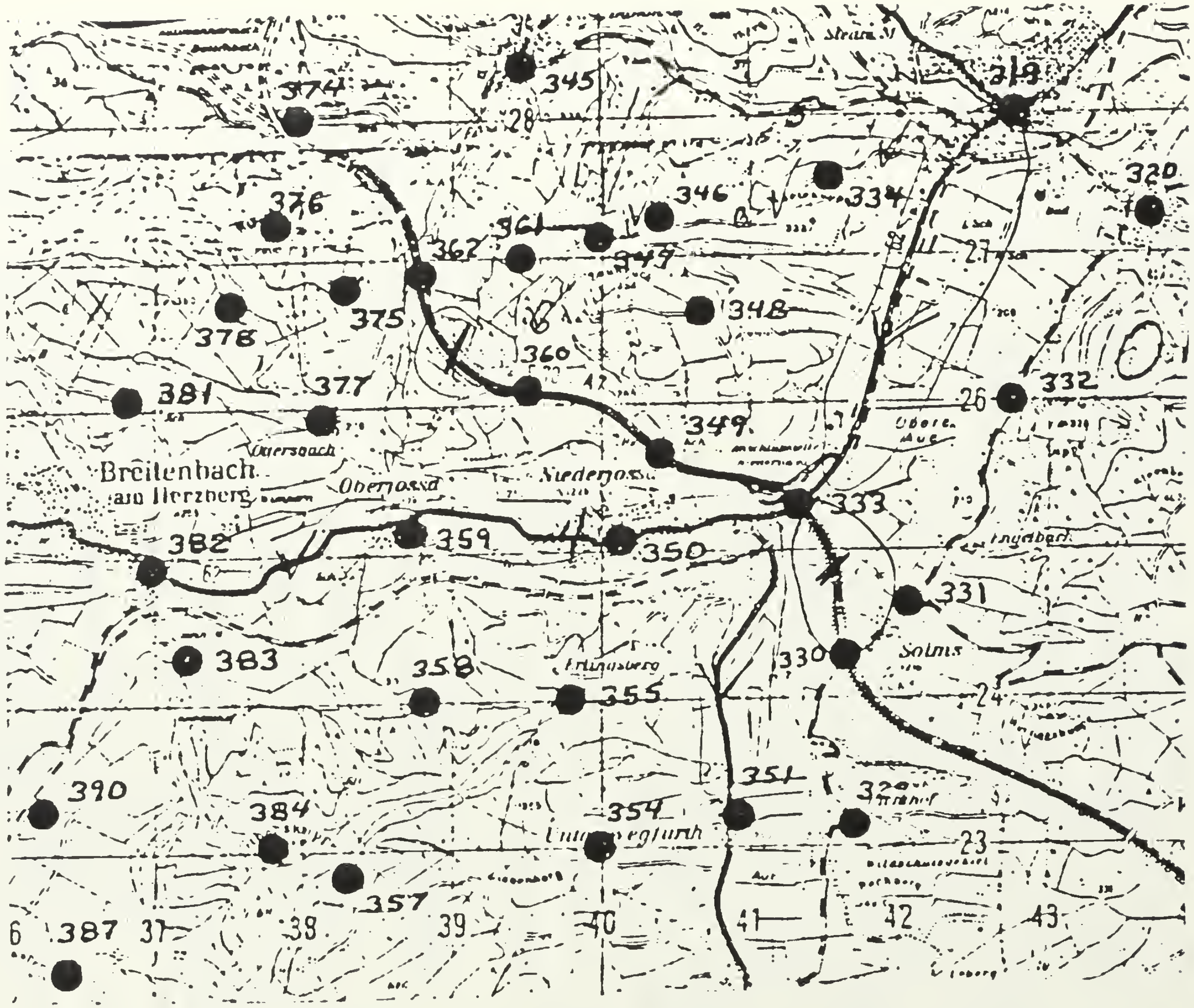

Figure 3.1
Nodes In 1-14th Sector

used to store the CRT coordinates for plotting a node in graphic output. The data item Section is used to store the number of the sector in which the node is located for the development of sub-networks. The data items Cost, and Prev are needed to implement the minimum path algorithm. Data items Section, Cost and Prev will be discussed more thoroughly in Chapters IV and V.

The array Node is used to store all the necessary data on the nodes in the network for implementing the two algorithms. In PASCAL any of the data items can be manipulated using the appropriate data item name. For example, Node[I].Section would contain the number of the sector in which node number I is located. Node[I].Base.Lat would contain the latitudinal coordinate of node number I. Table IV shows the data structures as they are implemented in PASCAL.

3. Arc Characteristics

The arcs in the network represent feasible routes of movement from one location (node) to another. For a route to be considered feasible, it must at least provide for the movement of dismounted troops. Ten characteristics are used to represent an arc: head node identification, tail node identification, type, length, width, off-road mobility type, width of off-road lane, maximum target acquisition range, and two elements for combat effects. These characteristics provide sufficient data for the algorithms to compute appropriate movement times from node to node.

TABLE IV

PASCAL NODE DATA STRUCTURE

<u>Record Types</u>

```
NodeRec = Record                   PlotRec = Record
    ID    : Integer;                   Base    : NodeRec;
    Lat   : Integer;                   Horz    : Integer;
    Long  : Integer;                   Vert    : Integer;
    Ntyp  : Integer;                   Section : Integer;
    Start: Integer;                    Cost    : Real;
                                       Prev    : Integer;

Nodes = Array[1..700] of PlotRec;
```

<u>Variables</u>

```
Node : Nodes;
```

The head node identification is the identification number of the node where the arc originates. The tail node identification is the identification number of the node where the arc terminates. The Type characteristic is an integer code for one of ten possible arc types as shown in Table V.

The width of the arc is an integer representing the number of lanes available for the movement of track vehicles. A lane is defined as the width necessary for the movement of a single track vehicle. Thus, an autobahn could have a width value of 4, because four tanks can move side by side down an autobahn. On the other hand, a forested area would have a width of zero, because tanks cannot move through heavily forested terrain.

TABLE V

ARC CODES AND CORRESPONDING TYPE

Integer Code	Arc Type
1	Autobahn
2	Autobahn and Railroad
3	Railroad
4	Concrete Road
5	Asphalt Road
6	Dirt Road
7	Forest
8	Open Country
9	Road and Railraod
10	Bridge,Tunnel

The off-road characteristic is an integer value representing the type or class of vehicle which the off-road terrain will support. Table VI shows the integer code and the type of vehicle it represents. The width of the off-road lane is the width in kilometers through which the terrain will support movement.

TABLE VI

OFF-ROAD CHARACTERISTICS

Integer Code	Type Vehicle Terrain Will Support
1	Heavy Tank
2	Medium Tank, Fighting Vehicle
3	Heavy Truck
4	Light Truck
5	Dismounted Troops

The maximum target acquisition range characteristic describes the greatest distance in kilometers at which enemy targets can be detected while on that arc. This element is used in lieu of identifying elevations to compute line of sight. It is a general estimate which is representative of the aggregate detection range along the entire arc. This further requires the arcs in the network to be directed arcs. If the elevation at one end of the arc is greater than at the other, the detection range will depend upon which direction a unit is traveling along the arc. Figure 3.2 shows the network for the 1-14th's sector superimposed over the map of this sector.

The two elements used for combat effects represent the number of friendly standard units of armorment (SUA) currently allocated to an arc, and the delay measured in time units incurred from obstacles and barriers placed on

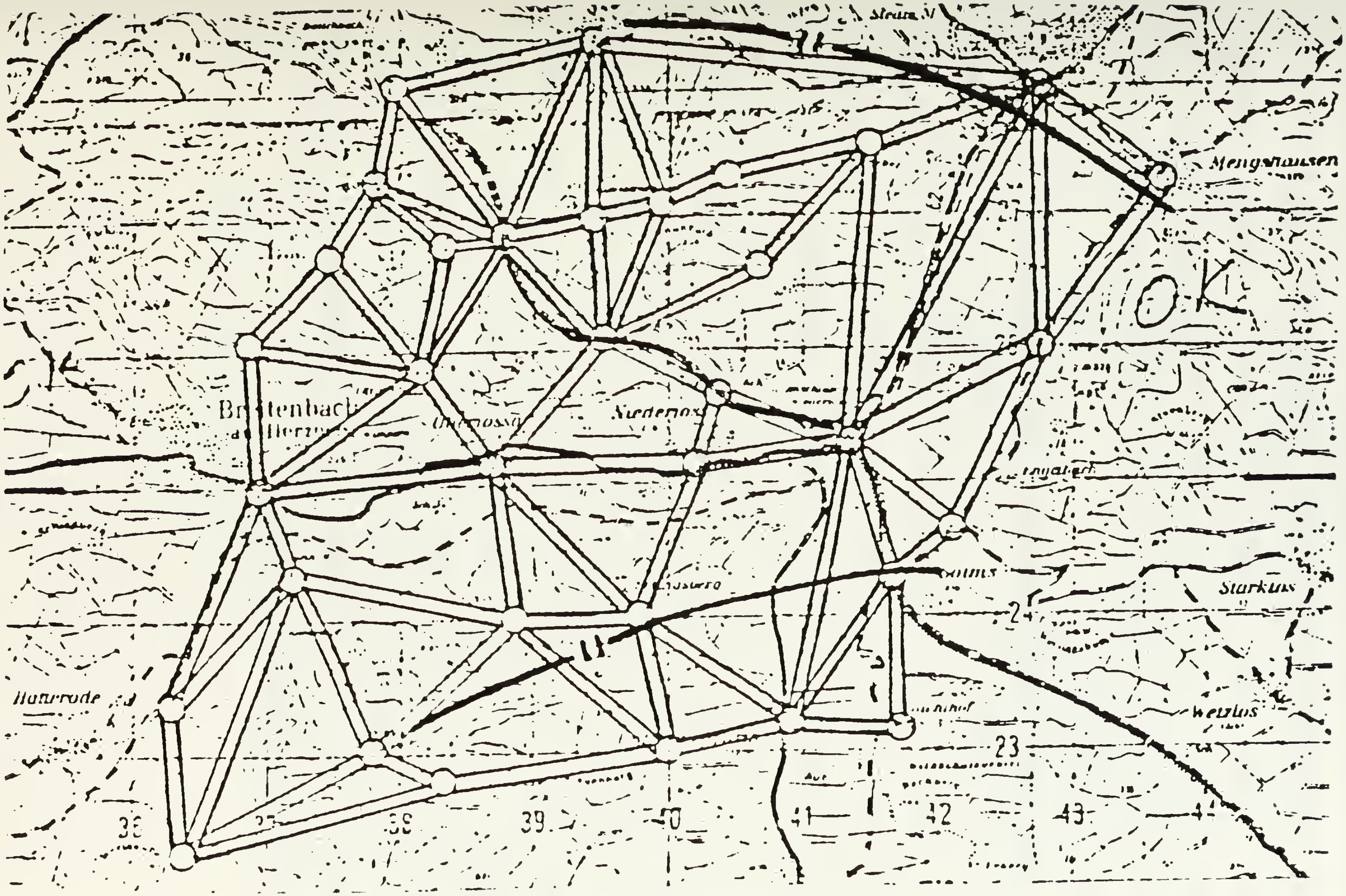

Figure 3.2
Network Representation of 1-14th Sector

the arc. The SUA value assigned to a unit is the Soviet method for comparing the relative combat power of a Soviet and U.S. force with their different weapon system configurations. In future implementations of the Airland Research Model this SUA measure will be replaced by the Generalized Value System.

4. Model Implementation of Arc Characteristics

In the model the arc representations are developed through the use of two record types, ArcRec and Arcs, and an array of pointers called AdjArr. The record type ArcRec is a direct PASCAL representation of the data describe in III-C-3. The record type Arcs consists of a pointer variable called base of type ArcRec, a variable for storing the required traversal time for the arc called time, and a pointer variable called next. These Arc records are then organized into a series of linked lists, with each list corresponding to a common head node. The array AdjArr is an array of pointers indexed by head node number with the corresponding variable being a pointer for the appropriate list of adjacent arcs. Table VII shows these data structures as they are implemented in PASCAL.

TABLE VII

PASCAL IMPLEMENTATION OF ARC STRUCTURE

Record Type

```
ArcRec = Record;                    Link = ^Arcs;
   Head  : Integer;
   Tail  : Integer;                 Arcs = Record
   Lent  : Real;                       Info : ArcRec;
   Typ   : Integer;                    Time : Real;
   Spee  : Real;                       Next : Link;
   Ofrt  : Integer;
   Lane  : Integer;                 AdjArr = Array[1,700] of Link;
   Widt  : Real;
   Acqu  : Real;
   Extr  : Real;
```

Variables

```
Adj   : AdjArr;
```

D. MODEL DATA FILE STRUCTURE

The network representation of the maneuver area is placed in two disk files, one for the arcs and one for the nodes. The two files are organized in an adjacency list structure. When read into computer memory this adjacency list structure is modified into the linked-list structure providing for more efficient use of internal memory. For a disscussion of adjacency list, linked-list structures, and PASCAL implementations of these data structures see Sedgewick [Ref. 8: pp. 166-189].

IV. UNIT PLACEMENT ALGORITHM

A. INTRODUCTION

In a mid-European battle the U.S. task force commander can expect to be outnumbered by three to one in the main battle area. To overcome such odds, he must develop a defensive plan which uses the advantages of the defender to their maximum potential. Two key steps in the development of such a plan are the proper allocation of combat power and the proper placement of fighting units. In this chapter, an implementation of the unit placement algorithm will be presented using the transportation network described in Chapter III. The modifications needed to convert the basic algorithm to computer usable form will be described, with a discussion of the PASCAL implementation of each step. A review of "shortest path" methods will be presented along with an example of the method used in the model. The chapter will conclude with a discussion of the results of a practical application of the algorithm to the scenario for Task Force 1-14 and a comparison of these results with the text solution.

B. UNIT PLACEMENT ALGORITHM

The Unit Placement Algorithm is designed to be used as a module which can be call at any time in the Airland Research Model to provide locations for the placement of the units of a battalion task force. Therefore, with each new battalion a different set of sector boundaries and list of company sized units is passed to the module. To provide for recurring calls to the module for different battalions, the original algorithm has been modified to create a sub-network of the overall terrain network based on the sector boundaries of the battalion. The Unit Placement Algorithm from Chapter III is modified as follows:

Inputs: Network G(V,E), nodes V, arcs E with their characteristics as described in Chapter III, a set of units with associated SUA values, and boundaries for the unit's assigned sector, enemy threat unit SUA value.

Outputs: An assignment scheme for the set of units to arcs in the unit's assigned sector of the network.

Step 1. Sort the units by sector and descending order of Standard Unit of Armorment (SUA).

Step 2. Select the next sector in which units have not been assigned.

Step 3. Create a sub-network of the overall network that describes the unit's assigned defensive sector.

Step 4. Compute the time required for the threat unit to traverse each arc.

Step 5. Select the unassigned unit within the sector with the largest SUA value.

Step 6. Determine the minimum time path for enemy movement through the sub-network.

Step 7. Determine the arc of the minimum time path which has the largest maximum effective range and allocate the unit to this arc. Ties are broken by selecting the arc closest to the FLOT.

Step 8. If all units in the sector have been positioned, go to Step 9. Otherwise go to Step 5.

Step 9. If all sectors have had their units assigned, Stop. Otherwise, go to Step 2.

The number of units assigned to a battalion task force is usually four and will rarely exceed seven. Therefore any simple sort routine is adequate to perform Step 1. The model uses a bubble sort for this purpose. With the unit data vector sorted, the looping logic of Steps 2 and 8, and Steps 5 and 7, is performed with a set of nested loops. Thus, the major problem in the algorithm implementation is performing Steps 3, 4, 5, and 6.

1. Creation of Sub-Network

The boundaries of each battalion task force's defensive sector are defined in the brigade's defensive plan. The purpose of these boundaries is to define the defensive zone of responsibility for the battalion task force. The boundaries are selected to contain one or more major avenues of approach through the brigade sector. Therefore, in a network sense, the lateral boundaries of a battalion sector will run roughly parallel to one or more sets of connected nodes extending from the FLOT to the sector rear boundary.

Within these boundaries, a sub-network must be created which describes the maneuver area in which the battalion must develop its plan of defense. This sub-network consists of the three categories of nodes and arcs. Category 1 nodes and arcs are the nodes and arcs within the sector boundaries. Category 2 nodes are nodes not within the sector boundaries, but connected to nodes within the sector boundaries by arcs. Category 2 arcs are the arcs connecting category 1 and 2 nodes, and connecting category 2 nodes. Category 3 nodes consists of two dummy nodes, called the supply node (node s) and terminal node (node t), which represent all the nodes to the front and rear of the battalion sector, respectively. Category 3 arcs are the arcs crossing the front boundary and going into the sector, and crossing the rear boundary and going out of the sector. The supply node is connected to the sub-network by all the arcs crossing the FLOT and the terminal node by all the arcs crossing the rear boundary.

The boundaries are treated as inputs to the battalion planning module. The information defining these boundaries is passed to the module as a vector or array, Bounds[I,J], of from two to ten pairs of coordinates. Bounds[I,J].YLoc and Bounds[I,J].Xloc make up the pair of coordinates for boundary point I in sector J. The pairs are ordered in this vector from least to largest longitudinal value. Thus Bounds[I,J] is always less then Bounds[I+1,J]. The pair of vectors, Bounds[I,J], and Bounds[I,J+1], make-up the latitudinal boundaries of each sector. A line connecting the set of pairs, Bounds[1,J] and Bounds[1,J+1], defines the rear boundary of the battalion sector. Likewise, a line connecting the set of pairs, Bounds[I_{max},J] and Bounds[I_{max},J+1] (where I_{max} is the index of the largest longitudinal point in the vector), defines the front boundary of the battalion sectors.

From this data, all the nodes of the network included in the sector can be determined geometrically or algebraically. In the model an algebraic implementation was used but a brief discussion of a geometric method is included because of its possible applications in further research. After determining the Category 1 nodes and arcs, their adjacent Category 2 nodes and arcs can be identified. Finally the two dummy nodes can be generated and the Category 3 arcs found.

The geometric method takes advantage of the fact that all the points on the boundaries must be defined as integer values to be displayed by the pixels of a computer CRT. A straight line drawn from any point within the boundaries of the sector must intersect the boundary an odd number of times. The cases of a point on the boundary, or a line that is drawn coincident with a boundary are treated as special cases. Using PASCAL this can be efficiently done for small sectors by representing the set of points on the boundary as an array. Recursive calls can then be made to a routine that checks the array and line for common values and increments the length of the line if an intersection is not found. Proper data structures for the array of points and sound search techniques for common values make the algorithm quite time efficient [REF. 9: pp. 315-317].

The algebraic method uses the set of points along the boundaries to compute the equations of the lines between each successive point. The coordinates of each node are then substituted into the appropriate line equation to determine if the node is above or below the boundary line. Following this procedure for each boundary line determines if the node is in the sector. To speed this procedure in the program, the slope and intercept of the line between successive points along the boundary are stored with the boundary data points in the array Bounds[I,J] as Bounds[I,J].slope and Bounds[I,J].b.

In the model the determination of the sector in which a node falls is performed by a procedure called Checksection. In this procedure, each node in the network is checked to determine if it is behind the FLOT by using the line defined by the end points of the boundaries. If behind the FLOT, the node is checked to determine if it is in front of the rear boundary of the sector. If in front of the rear boundary, the longitude of the node is checked sequentially with each point in the upper and lower sector boundaries. When the node's longitude is less than or equal to a point in a boundary, then it is substituted into the line equation to determine if it is above or below the line. If below the upper boundary and above the lower boundary, the node is in the sector and is coded with the identity of the sector in the variable, Node[I].Sector. The program is set up to process up to seven battalion sectors, and therefore, the nodes will be screened to determine if they are in any of the possible seven sectors.

With all the nodes coded as to the associated sector and the adjacency list data structure, it is a simple matter to create the sub-network. The Category 1 nodes are all the nodes coded with the sector code. The Category 1 arcs are the associated arcs defined in the adjacency list. The Category 2 nodes are found by checking each node adjacent to the Category 1 node. If it is not within the sector, it will not have a corresponding sector code, so it is a Category 2 node. A special code is then given to these Category 2 notes to distinguish them. The Category 2 arcs are the arcs from the adjacency list connecting Category 2 nodes, and connecting Category 1 and Category 2 nodes. Category 3 nodes are then found by identifying the Category 2 node in front of the FLOT or behind the sector rear boundaries. These nodes are then redesignated as s or t respectively. The Category 3 arcs are only the arcs in the adjacency list connecting Category 3 nodes to Category 1 nodes. It is important that the direction of the arc is determined for Category 3 arcs. Only those arcs going into the sector from s and out of the sector to t are included. A separate list of Category 3 arcs is maintained and their lengths are defined as zero. The PASCAL implementation of this process simply defines variables First and Last as pointers to linked lists of the connecting arcs. In using this method only two new variables are needed, First and Last, because the original adjacency list is used for the sub-network as well.

2. Arc Traversal Time

For the purpose of this planning model, it is not necessary to develop extremely accurate simulations of attacking force movement. Rather, only general estimates of expected movement rates based on unit size and type, and the characteristics of the terrain being crossed are sufficient. Two methods, a table look-up method and a set of movement equations, were tried.

In the table look-up method, data on estimated movement rates based on available roads and off-road terrain was organized in an array. Based on the arc characteristics, an estimated speed was extracted from the array. Then using the length of the arc, the amount of time required to travel the length of the arc was computed.

The set of movement equations were developed in previous work on the attacking force planning model [Ref. 10: pp. 118-122]. Based on this work the minimum time to traverse an arc, T_{min}, was computed using the equation:

$$T_{min} = (L /(R \times K_r \times S_f)) + (D /(K_r \times S)) \quad \text{(eq. 1)}$$

where:

L = unit column length R = routes available

K_r = coefficient of route availability

S_f = off road movement rate S = on road movement rate

D = distance to travel

K_r, the coefficient of route availability, is a measure of the potential actual daily traffic flow to operational and tactical road capacity. For the scenario being used, K_r has a constant value of .9.

The number of routes available is computed using the equation from the attacking force planning model:

$$R = (S/S_f)(N (L_v + L_v') + (M-1)L_c')/(1000\ K_r(TS-D)) \qquad \text{(eq. 2)}$$

where:

S, S_f, D, and K_r are defined as above

L_v = vehicle length

L_v' = interval between vehicles

L_c = unit column length

N = number of vehicles in unit

M = number of units T = time available

Because of the assumption that attacker force battle formations are fixed within the MBA, the movement parameters M,N,T,L_v,L_v', and L_c are constants. For the case of an attacking regiment, equation (2) can be simplified to:

$$R=2436(S/S_f)/ 1000 \qquad \text{(eq. 3)}$$

The value for the on-road movement speed, S, is computed using:

$$S = 0.475\ V - 17.0 \qquad \text{(eq. 4)}$$

The value for V varies from 40 to 120 based on the type of road. Table VIII shows the relationship between the arc code and the value for V.

TABLE VIII

ARC CODES AND CORRESPONDING VALUES OF V

Arc Code	V
1,2	120
3	36
4	100
5	90
6	75
7,8	40
9,10	90

The value for the off-road movement rate is determined by the equation:

$$S_f = 0.233\ V - 5 \qquad \text{(eq. 5)}$$

The values for V for this equation were determined by the equation:

$$V = 30 + 90\ W \qquad \text{(eq. 6)}$$

where :

W = the off-road lane width in kilometers

Equation (5) and the values in table VIII were derived to approximate the table values arrive at in the original work [Ref. 10: pp. 119-120].

Though the table look-up method produced a faster running algorithm, the set of movement equations was used because they produced a much better approximation. Typical results from the equations produce traversal times for a one kilometer arc of one minute (40 miles per hour) for best conditions to 60 minutes (1 mile per hour) for the worst conditions.

3. Minimum Time Path Determination

The determination of the minimum time path through the sub-network is one of a class of many such problem often referred to as "shortest path" network problems. The general shortest path problem is to determine the least cost route through a network starting at node S and ending at node T. The cost of a route is some function of the characteristics of the arcs and nodes that make up the route from S to T. In the case of this minimum time path problem, the cost of traversing an arc is the amount of time it takes an attacker unit to traverse the arc. The cost of the route is the sum of the costs of all the arcs in the path from the supply node to the terminal node.

Before selecting a method of finding a shortest path, the network must be examined to insure that there is in fact a solution in all cases. Because no arc in the network will have a negative cost associated with it, the addition of another arc to any path will never reduce the total time traveled. Therefore, negative cycles cannot exist in the network. The only arcs which have a zero cost are those leaving the supply node and entering the terminal node. Furthermore, boundaries are selected to run parallel to avenues of approach through a sector, so it is valid to assume that there will be at least one set of connected nodes which extends laterally through the sector. Thus, the method of construction of the sub-networks insures there will always exist at least one path between supply and terminal nodes. So there must be a solution to the shortest path problem, and there will not be any cycles in a minimum path (no node will be visited twice). If the assumption that boundaries are drawn which include a connected path from the start to the terminal node is invalid, a solution may not exist to the problem.

Because of the many application for this class of problems, there are many algorithms available for its solution. Most of these algorithms consist of two procedures: a label correcting procedure and a search procedure.

In the label correcting procedure each node is initially assigned an infinite cost with the exception of the starting node, s, which is given a cost of zero. Letting c(v) be the cost assigned to node v, d(v,w) be the cost to traverse the arc from node v to node w, and pred(v) be the node previous to v in a path, then the following rule is applied to change the costs associated with node w:

$$\text{If} \quad c(v) + d(v,w) < c(w) \qquad \text{(eq. 7)}$$

$$\text{then} \quad c(w) = c(v) + d(v,w) \text{ and } pred(w) = v.$$

Though inefficient if applied indiscriminately, if this rule is continuously applied until no cases of equation (7) being true can be found, the chain of pred(w) until pred(v)=s will describe the minimum path from every node in the network to the starting node, s.

The search procedure is used to decide in which order the nodes are to be scanned to apply the labeling rule. This step is where most algorithms differ and also where the efficiency of the algorithm is achieved. In most cases one of three search techniques are used: Dijkstra's algorithm, depth first search, and breadth first search, but many hybrid techniques are also available. Dijkstra's algorithm gives priority of search to the adjacent node which is the shortest distance away. Depth first search gives priority to the most recent node searched. Breadth first search gives priority to the oldest node searched. The breadth first search method was selected for use in the program. This is recommended by Tarjan [Ref. 7:p. 91] as a good method in the case of this type of single source problem. To determine the next node to be searched in the breadth first search a first-in, first-out queue is used. This queue is implemented as a circular array to eliminate the problem of overflow. For further discussion of the use of a circular array as a queue see Tenenbaum [Ref. 8: pp. 158-165]. Using the notation above, the shortest path finding algorithm can be stated:

```
Input: Sub-network G(v,e) with nodes v, arcs e, and arc
        costs c(i), with start node s, terminal node t.
Output: Shortest path from s to all nodes in G.

Step 1. Initialize: a) set all labels to a very large value
                              c(i) = infinity

                    b) set all predecessor value to -1
                              pred(s) = 0

                    c) set cost of starting node to zero
                              c(s) = 0

                    d) place starting node in the queue
                              queue = {s}

Step 2. For each node w adjacent to the node v at the top
        of the queue
          { if    c(v) + d(v,w) < c(w)
            then  c(w) = c(v) + d(v,w); pred(w) = v

            { if w is not in the queue  (ie. pred(w) > 0)
              then pred(w) = - pred(w);
                   add w to the end of the queue }}

Step 3. Remove v from the front of the queue
                 pred(v) = - pred(v)

Step 4. If queue is empty, Stop. Else go to Step 2
```

When the queue is empty, each node in the network will have a cost assigned which represents the minimum cost for all possible paths from the node to the starting node,s. The minimum path from any node to the start node can then be found by tracing the chain of predecessor values back to the start node. Thus, to find the minimum path through the sub-network, the algorithm is applied using the dummy supply node as the starting node. When the algorithm is completed, the minimum time path is defined by the chain of predecessor values from the terminal node, t, to the supply node.

a. Time to Traverse Interdicted Arcs

When a defender unit is placed on an arc, the SUA value of the unit is added to the current value of the arc characteristic EXTR. For interdicted arcs, the traversal time for attacher units must not only include travel time on the arc, but also the time required to overcome any defender units on the arc. To compute this additional time for a battle, a Lanchester linear law formulation is used. The formulation was developed to obtain a lower bound on expected battle lengths for the attacher force planning model [Ref. 10: pp. 150-156] and its use here will provide continuity of results for both defender and attacher forces. The length of time, T, for an attacker force to overcome a unit is computed using the equation:

```
T = ( 1 / (U1-U2)) *
     ln (( U1-(1-FSP)*U2) / ( ESP*U1))             (eq. 8)
```

where :

U1 = (Attacker SUA /Defender SUA) (Attacker Rate of Fire)

U2 = (Defender SUA /Attacker SUA) (Defender Rate of Fire)

FSP = Defender Break point (expressed as a fraction of initial strength)

ESP = Attacker break point

Attacker Rate of fire = .0045

Defender Rate of fire = .0015

Typical results from this equation produce battle lengths from 20 to 60 minutes depending on the size and number of the Defender units placed on an arc.

4. <u>Determining of Unit Placement</u>

The minimum time path through the network is defined from the chain of predecessor nodes from the terminal node to the supply node resulting from the shortest path algorithm. This chain is then searched to find the arc which has the largest target acquisition range and is closest to the FLOT. A very direct approach is used to accomplish this. Starting at the terminal node, the largest acquisition ranges so far encountered is compared with that of the arc connected to its predecessor. The arc with the largest range encountered in the search is identified for the placement of the unit. In the case of comparisons which result in a tie, the most recent arc searched is selected.

C. VALIDATION OF RESULTS

In comparing the results of the model with the approved solution from the C&GS literature, the thesis objectives must be kept in mind. Therefore, the analysis will focus on two areas: validity of the algorithm results, and the applicability of the network formulation . To determine the validity of the results of the algorithm, exact correlation between map positions of units should not be expected. To achieve precise unit locations in X,Y would require a much greater density of arcs and nodes than that which exist in the current network. Such a density would defeat the benefits of using a network terrain formulation as opposed to past techniques. There should, though, be a reasonable correlation between the positions. The same functions of directing fires on the enemy and restricting enemy movements over the same portion of the battlefield should be able to be performed. The same force ratios should be achieved in the battle area. Also the same general scheme of maneuver and defense should be possible. Therefore, valid results may be achieved from the model that do not exactly represent the text solution, if the model results represent tactically sound, viable alternatives.

To justify the applicability of the overall methodology, if the results of the algorithm are not valid they should be correctable by minor modifications to the network, the values of the arc and node characteristics, or the algorithm. Further, the model should provide solutions to the positioning problem fast enough that scaling up the model for the planning of all the battalions in a corps is feasible.

The difficulty of determining objective answers to these criteria is further increased because many of the questions about the resolution requirements of the Airland Research Model have not yet been resolved in previous research. Therefore, the analysis of the results must be subjective in nature. A benefit of the results is that they will provide answers to the resolution capabilities of this approach.

1. <u>Comparison of Results</u>

The text solution to the 1-14th scenario places the units as shown in Figure 4.1. The solid ovals define the area over which the units will be spread when initially deployed. The hashed ovals define secondary positions. The following battle plan is described in the solution. Tm ALFA is to occupy and defend B4 initially, and on order move to B7. Tm CHARLIE is to occupy and defend B5 initially, and on order move to B8 and B11. Tm MECH is to occupy B2 initially, and on order move to B10 and B9. Co. B is to occupy B3

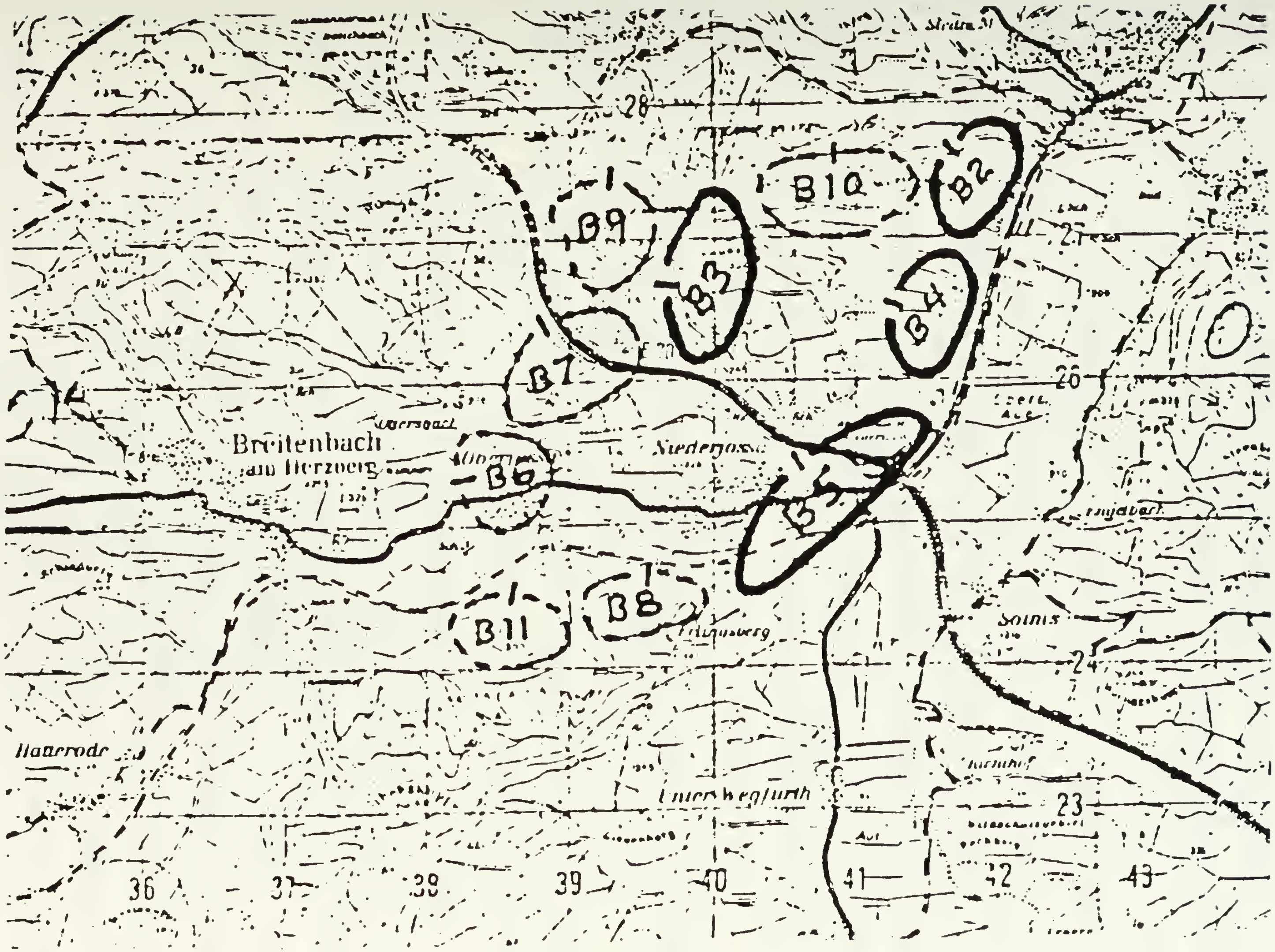

Figure 4.1
Proposed Unit Locations

initially, and on order move to B C2 (not in this sector). Priority of fires is to Tm CHARLIE, priority of engineer support is to Co. B, Tm Charlie, Tm MECH, and Tm ALFA in that order. The defense in sector is keyed on B3 [Ref. 6:pp. 9.9-9.11].

The intent of this scheme of maneuver is to conduct an initial engagement along the FLOT attriting the attacker forces as much as possible while holding defender losses to a minimum. The attacker force will be channeled through the open terrain corridor in the north of the sector using barriers and obstacles. Once deep into the valley in the center of the sector, the attacker force's mobility and maneuverability will be hampered. The defender force will conduct a strong point defense at B3 supported by the positions on the hillside of the valley at B10 and B7 and destroy the remaining attacker force.

The results of the model's unit placement is shown in Figure 4.2. The numbered arcs define the location and priorities of the unit placements. The placement of the first unit along arc (330,333) corresponds with the proposed placement of Team Charlie in B5. The location of the second unit along arc (319,333) corresponds with the placement of Team Alpha and Team Mech in B4 or B2. The placement of the third unit along arc (351,333) corresponds again to the location of a second unit at B5. The positioning of the

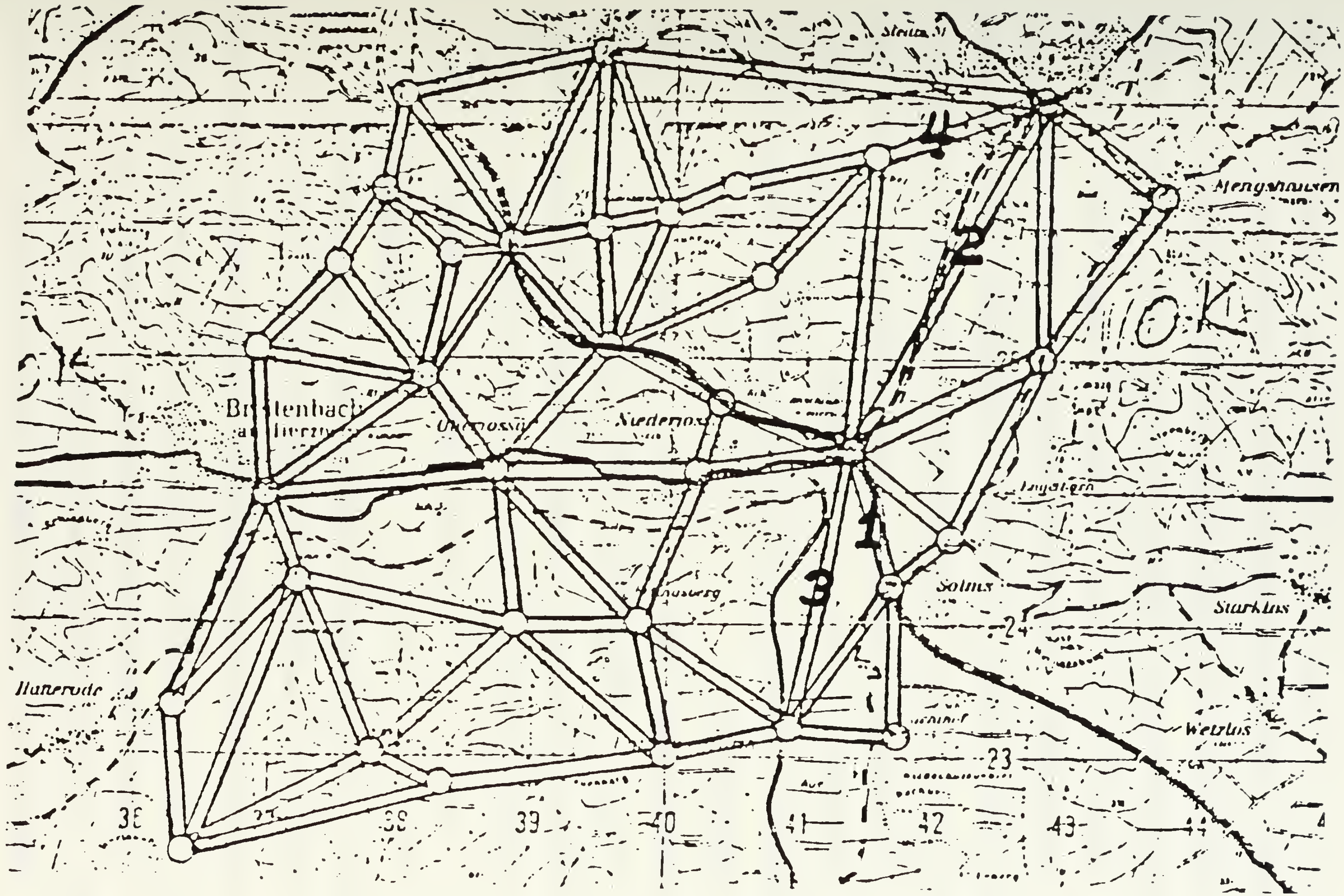

Figure 4.2
Model's Unit Placement

fourth unit to arc (319,334) corresponds to the location of a unit in B2. The model does not locate a unit at B3.

The primary avenues of approach through the sector are along Highway 60 through the Jossa river valley and through the open terrain in the northern portion of the sector. The variants to these avenues are the directions in which the river along the FLOT is crossed: by crossing the bridge to the front of the sector, by crossing the river bed, or from the roads to the north and south. The model identified paths through both avenues of approach and identified each of these variants, allocating a unit to each variant accordingly.

2. Algorithm Run Time

Because the battalion task force sectors within a corps maneuver area are all approximately the same size, they will have roughly the same number of nodes and arcs as the sector used in this scenario. Thus, the amount of time required for the algorithm to run will be very similar for each sector in the corps. For each sector, the creation of the sub-network, the computation of the arc traversal times, and the determination of the minimum path for each unit are independent processes within the algorithm. Thus, the run time of the algorithm will be the sum of the run times for each step. The most time consuming process in the algorithm is the creation of the sub-network. The network for the corps area has 516 nodes and 2752 arcs. Creation of the sub-network for this scenario, took approximately 25 seconds. For small sectors, in terms of the number of nodes and arcs, the run time for this process is approximately linear with respect to the number of nodes in the overall network. The sub-network used in the scenario has 22 nodes and 92 arcs. The computation of traversal times is linear with respect to the number of arcs in the sub-network. For the sub-network used, this takes approximately 7 seconds. The determination of each shortest path and unit placement has a run time with an upper bound proportional to the square of the number of nodes in the sub-network [Ref. 7: p 93]. This takes approximately 3 second for each unit placement. The overall run time for the algorithm placing four companies is approximately 45 seconds per sector. Though this is too long if scaled up to a corps, a mainframe system can reduce this to very reasonable run times.

2. Conclusions

In comparing the results to determine the validity of the algorithm, two differences are apparent: units along the FLOT are shifted to the south and the model did not place a units at B3. It must be noted that the model results present a feasible alternative to the text solution. The model placed all units roughly on a line from node 319 to node 351. The positions would provide for cover and concealment in the village at node 333 and on the hilltop along the west side of the river. From these positions the units can provide supporting fire for each other, and fire at maximum range on attacker forces approaching from the east.

Of primary concern is the model's placement of three units around node 333 which shifts the units to the south. Though the arcs going into this node have the capacity to support the movement of a battalion or larger size unit, the subsequent arc on the shortest path leaving node 333 has the capacity for only one battalion size unit. Therefore, placing one unit on the arc leaving node 333 is sufficient. Until the three primary arcs, (319,333), (330,333), and (351,333) entering node 333 have been interdicted, no shortest path that does not include node 333 will be found by the shortest path algorithm. The addition of other arcs or nodes to the north will not solve the problem. Modifying the movement rate functions to increase the movement rate along the roads and decrease it across the bridge could result in the selection of arc (319,334) for the placement of a unit before arc (330,333). To do this, however, would require increasing the movement rates for arcs (330,333), (331,333), and (332,333) by a factor of 100 which is not considered feasible. Two alternatives which could easily be implemented are to model the effect the placement of a unit has on neighboring arcs or to look at the relationship of flow capacities of the arcs in the vicinity a unit's placement.

When a unit is placed on an arc, it really should result in an increase in movement rate on all arcs within the acquisition range of the unit's weapons. Further, this increase is a function of the distance from the location of the unit. This same problem will be encountered in the modeling of the effects of indirect fire weapons, chemical weapons, and nuclear weapons. To model this effect, boundaries are drawn around the arc on which the unit is located. These boundaries are a distance from the arc equal to the effective range of the units weapons. In the same manner as the sub-network was created, all arcs within these boundaries are identified. Then an SUA value is assigned to these arcs in the same manner as in the unit placement. The only new procedure required for this is a routine to compute the a set of points describing the boundary.

Looking at the movement capacity of the arcs around a unit's placement can also provide a means of overcoming this problem. When a units is placed on an arc, the tail node of the arc is searched for all arcs entering the node from the direction of the FLOT and leaving in the direction of the sector rear boundary. The SUA value of then unit is assigned to all arcs in the set of entering or leaving arcs with the smallest total capacity. The information for computing capacities is already available in the arc characteristics, so the only new procedure required is to identify entering and leaving arcs.

The failure of the model to locate a unit at B3 can be attributed to the fact that the rule on which the algorithm is based is only for the placement of units and not the allocation of units. Therefore, all units passed to the algorithm as input will be placed as far forward in the sector as possible. The text solution allocates only three units to this mission. The unit at B3 is placed there only after enough force is allocated to the FLOT to achieve proper force ratios. The selection of positions such as B3 can be selected by simply moving the forward boundary back behind the initial positions and running the algorithm a second time. Therefore, by adding an allocation mechanism to the algorithm, the methodology can be simply extended to the planning of alternative positions. The allocation mechanism can be be a check for proper force ratios at the FLOT at which time the forward boundary is moved back 1000 meters.

From the above discussion it is clear that the algorithm falls somewhat short of what is needed to use in a model for a unit placement planning module. The algorithm fails to consider the capacity of avenues of approach to support the movement of forces and therefore may over allocate forces. This problem can probably be overcome by small modifications to the mechanism by which the assign of a unit to an arc is treated. The need to implement either of the suggested modifications can only be answered when final decisions on the required resolution are made. For a corps level model to have a company sized unit located 500 meters "out of position" is not considered a significant problem. The algorithm does provide a good starting point for a unit placement module by providing sound tactical positions for the placement of units. With the addition of procedures for deciding on the proper allocation of units it can easily be expanded to the planning of secondary positions. Further research is need to define methodologies for the selection of the optimal allocation of units and positioning schemes as a result of the feasible locations identified by this algorithm. When converted to a mainframe system, the algorithm will be efficient enough for scaling to corps level.

The results provided by this algorithm for the placement of units shows great promise for future uses of the terrain network methodology. With only a few data items to represent the terrain, the simple Unit Placement Algorithm provides feasible solutions for locating units in a tactical scenario. Possibly of more importance is the fact that the terrain network representation of a brigade size maneuver area can provide resolution of the battlefield down to several hundred meters and still operate efficiently within the constraints of a micro-computer.

V. ENGINEER ASSET PLACEMENT ALGORITHM

A. INTRODUCTION

The Airland Battle doctrine dictates the use of engineers to support the maneuver forces in four primary missions: mobility, countermobility, survivability, and general engineering. In the initial planning of defensive operations,the proper utilization of engineering assets in the countermobility and survivability roles is critical. In the countermobility mission, the engineer assets are employed in the construction of obstacles which disrupt, delay, and kill the enemy. This increases the time for target acquisition, thus enhancing the effectiveness of weapons. In the survivability mission, engineer assets are utilized for the construction of earth berms, dug-in positions, and overhead protection. This reduces the enemy capability to detect the defender and to bring effective fire on the defender's positions. Therefore, the engineers play a crucial role as a member of the combined arms team.

The nature of the engineer asset placement problem is to efficiently employ limited assets for the construction of many different types of obstacles for countermobility and barriers for survivability. The type of obstacle or barrier to be deployed is dependent upon terrain and other features such as roads and bridges within the battle area.

In this chapter, the implementation of the engineer asset placement algorithm will be discussed. The algorithm will be restated in a form suitable for computer implementation. The steps of the algorithm will be presented individually along with the method of PASCAL implementation. Several modifications to the algorithm which enhance the placement of obstacles will be discussed. The chapter will be concluded with a comparison of the model solution associated with the 1-14th scenario with the proposed C&GS solution.

B. Engineer Asset Placement Algorithm

Like the Unit Placement Algorithm, the Engineer Asset Placement Algorithm is designed to be a stand-alone module. The module can be called to plan the placement of engineer assets for any battalion within the corps. To achieve this, the original algorithm must be modified so that it can create a sub-network from the boundaries of a given battalion sector. The modified algorithm is stated as follows:

Inputs: Network G(V,E), nodes V, arcs E with associated characteristics as stated in chapter III, a set of engineer assets with their relative costs, a set of obstacle construction techniques with their required assets for construction and increase in delay time as a result of placement, enemy threat unit.

Outputs: Set of obstacles with the arcs to which they are assigned.

Step 1. Select the next battalion sector.

Step 2. Create a sub-network from the network G, that describes the battalion sector.

Step 3. Compute the time required for the threat unit to traverse each individual arc in the sub-network.

Step 4. Determine the minimum time path through the sub-network.

Step 5. For each arc, i, in the minimum time path, define a set, O_i, of obstacles for interdicting arc i. If no obstacles are found for any arc in the minimum time path, go to Step 9.

Step 6. From the sets of O_i, find a subset, F_i, of feasible obstacles for which there are sufficient remaining assets to construct the obstacles. If no feasible obstacles exist for any arc in the minimum time path, go to Step 9.

Step 7. From the subset of feasible obstacles for each arc,

F_i, select the obstacle, F^*, for arc i^* which has the largest ratio of delay time to cost.

Step 8. Assign additional delay time associated with technique F^* to arc i^* and reduce the assets available by the amount needed to construct F^*.

Step 9. If all sectors have had their available assets assigned, Stop. Otherwise go to Step 1.

In this algorithm, Steps 1 through 4 are performed in the same manner as with Unit Placement algorithm described in Chapter IV. The algorithm is implemented using two loops. The loop, Step 1 and Step 9, checks to determine if the placement process has been completed for the assets in all the sectors. The loop, Step 4 and Step 8, insures that all the assets for the current sector have been placed or that no feasible placement exists on the current minimum time path. In the model this is easily implemented using a pair of nested While loops.

After the current minimum time path has been found in Step 4, the arcs of this path are scrutinized individually for the best method of interdiction. To facilitate this process, the engineer assets are aggregated into obstacle standard packages, and further into Standard Operating Procedure Tables.

An obstacle standard package consists of the assets required to construct a specific obstacle. For example, a tactical minefield is an extensive minefield of 100 meters in length or more, which can delay or block enemy penetrations. One method of laying a tactical minefield is by using the M57 mine dispensing system. The material required to place a 100 meter tactical minefield is aggregated into a package called M57 standard package. The engineer assets may then consist of 10 M57 packages. Also associated with an M57 standard package is the manpower requirement to place the minefield using the M57 system. The engineer assets must, therefore, also include the total manpower available. For this model the manpower assets are measured in units of squads. Each standard package is also given a measure of relative cost. This relative cost is a measure of the total value of the assets in the package and its manpower requirements with respect to the assets in all other packages.

To determine the method to be used and the assets required to create an obstacle on a terrain feature, a Standard Operating Procedure (SOP) Table is used. The SOP Table consists of an entry for each category of terrain features that maybe encountered. For each category, the methods available for creating obstacles on the terrain feature are listed. Associated with each method is a listing of the quantity of standard packages needed to construct the obstacle, the delay to enemy movement time resulting from the obstacle, and the total relative cost of the assets used. For a further discussion of the construction and use of SOP tables and engineer asset packages see Kazimer [Ref. 4:pp. 31- 46]. In the module, the SOP Table is represented as a two dimensional array, with one dimension defined by the categories of terrain features corresponding to arc characteristics and the other dimension is the method of constructing an obstacle. If an obstacle is appropriate for the interdiction of a terrain type, a 1 appears in the corresponding row (obstacle type) and column (terrain type) of the table. The assets required for the obstacle can then be read from the right side of the table. Table IX is an example of the SOP Table as implemented in the module.

With the assistance of the SOP Table, Steps 5 and 6 can be efficiently performed. For each arc in the minimum time path, the assets required for each possible interdiction method are read from the SOP table. These requirements are compared with the remaining assets available to determine if the method is feasible in terms of the remaining assets. If feasible, the delay time versus relative cost ratio is computed. If this ratio is greater than any previously computed ratio for the arc, then the new method is selected.

TABLE IX
SAMPLE SOP TABLE ARRAY

OBSTACLE TYPE	ARC TERRAIN CODE 1	2	3	4	5	6	7	8	9	10	STANDARD ASSET PACKAGE QUANTITY Squads	Dozers	Brdg Dem	M180	MFJ	MOPMS	Fuel	COST	DELAY
Blow Bridge	0	0	0	0	0	0	0	0	0	1	1	0	4	0	0	0	0	1	1.5
Block Primary Rd (100m)	1	0	1	0	0	0	0	0	0	0	2	0	0	2	0	0	0	2	.5
Block Secondary Rd	0	0	0	1	1	1	0	0	0	0	1	0	0	1	0	0	0	1	.25
Block Secondary Rd	0	0	0	1	1	1	0	0	0	0	1	0	0	1	0	1	0	2	.75
Block Secondary Rd (100m)	0	0	0	1	1	1	0	0	0	0	1	0	0	1	1	1	0	4	.75
Block Open Field (300m)	0	0	0	0	0	0	0	1	0	0	3	0	0	0	3	0	0	3	.75
Block Open Field (300m)	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	3	3	.1

This process results in a cost effective method of interdiction for each arc in the minimum time path. Step 7 compares the delay/cost ratios of the obstacles on the arcs along the path to find the arc with the largest of these ratios. Step 8 assigns the delay time associated with the obstacle to the arc.

As stated in Chapter II, the original rule made no attempt to have the obstacles covered by fire. This is an important feature in the selection of obstacle positions because clearing obstacles while under heavy fire greatly increases the delay associated with the obstacle and the effectiveness of weapons. The stopping criteria for the completion of the positioning process in each sector may result in many of the assets not being used even though feasible obstacle placements still exist. Therefore, several modifications were added to the original algorithm.

In an attempt to bring the placement of obstacles in line with the placement of units, thus covering obstacles by fire, priority is given to the selection of arcs close to the FLOT. As with the unit positioning, this was done by breaking ties by selecting the most forward arc. When units are placed on or close to the FLOT, their fires reach as far as 3000 meters forward of the FLOT. Therefore, in the initial battle positions, obstacles maybe placed far forward the FLOT. To allow the algorithm to take into account those arcs covered by fire forward of the FLOT, the lateral boundaries of the sector must be extended beyond the FLOT. It was found that extending these boundaries 1000 meters is sufficient.

To make sure that all possible assets are allocated, in Step 5 when no obstacles are found, the arc with the lowest ratio of delay time to cost is given a large delay time. Then the algorithm returns to Step 4 to compute an alternate path. When no arc can be found that does not have a delay time assigned to it, or all the assets have been used as determined in Step 6, the algorithm then goes to Step 9.

C. Validity of Results

The focus of the analysis of the model results must revolve around the thesis objectives of determining the validity of the algorithm and the applicability of the network methodology. As with the Unit Placement Algorithm, the results of the Engineer Asset Placement Algorithm should not be expected to produce exactly the same map locations for the obstacles as the C&GS solution. Again however, a reasonable correlation should exist and the same scheme of fire and maneuver should be supported by the obstacles. The network methodology should provide run times which will support the scaling up of the model to corps level and erroneous results should be correctable by changes to the values of the arc and node characteristics or minor modifications to the network. Unlike the Unit Placement Algorithm, the Engineer Asset Placement Algorithm must be able to take into account obstacles which have been preplaced by higher levels of command or have been placed in the sector prior to the unit's arrival. This requirement is a result of the hierarchical structure of the model.

1. Comparison Of Results

The proposed placement of obstacles in the C&GS solution is shown in Figure 5.1. The obstacles in the C&GS solution are utilized to support the primary battle positions along the Fulda River, the strong point position on the northern avenue of approach, and to restrict movement along Highway 60 on the southern avenue of approach. All the bridges in the sector have been identified for demolition and the primary and secondary roads in the sector have been severed through the use of craters or ditches. The demolition of bridges and road obstruction may or may not take place depending on future results of the battle. These demolition points, craters, and ditches are identified as dots in Figure 5.1. The terrain forward of the battle positions has been fortified by placing minefields to slow the enemy movement. Minefields are identified by the dark rectangular shapes in Figure 5.1. These minefields can be covered by fire from the battle positions. Thus the engineer

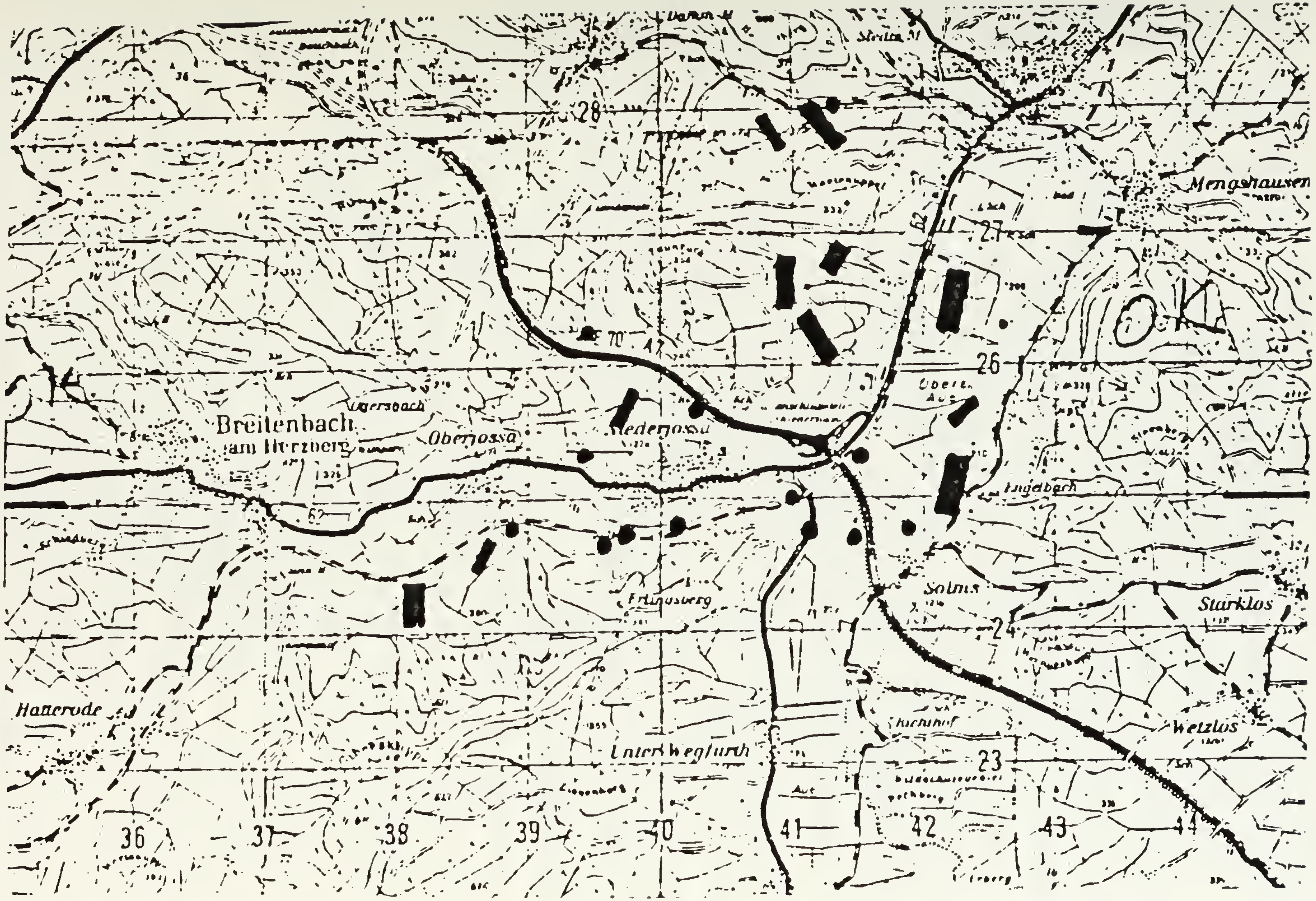

Figure 4.1
Proposed Obstacle Locations

assets have been allocated in such a manner as to enhance the scheme of maneuver for the task force.

Figure 5.2 shows the model's placement of obstacles in the sector. A D represents the placement of ditches and craters, a B represents the demolition of a bridge, and an M represents the placement of a minefield. The model places minefields along the Fulda River where they can be easily covered by fire from the units located on the west bank of the river. Minefields are also located along both avenues of approach through the sector. The three bridges in the sector are identified for demolition and the primary and secondary roads are identified for placement of ditches and craters. The model does not locate minefields in the southwest corner of the sector and places fewer obstacles in the sector.

2. Algorithm Run Time

Because of the similarity of the Engineer Asset Placement Algorithm and the Unit Placement Algorithm, the steps of the algorithms have comparable run times. The only differences are the number of times the shortest path step is visited and the mechanism for locating the arc for obstacle placement. The time to determine the shortest path and place an obstacle is approximately the same (3 seconds) as in the Unit Placement Algorithm. This sequence is visited between 5 to 25 time for each sector in the engineer problem, where as the unit placement problem will visit the

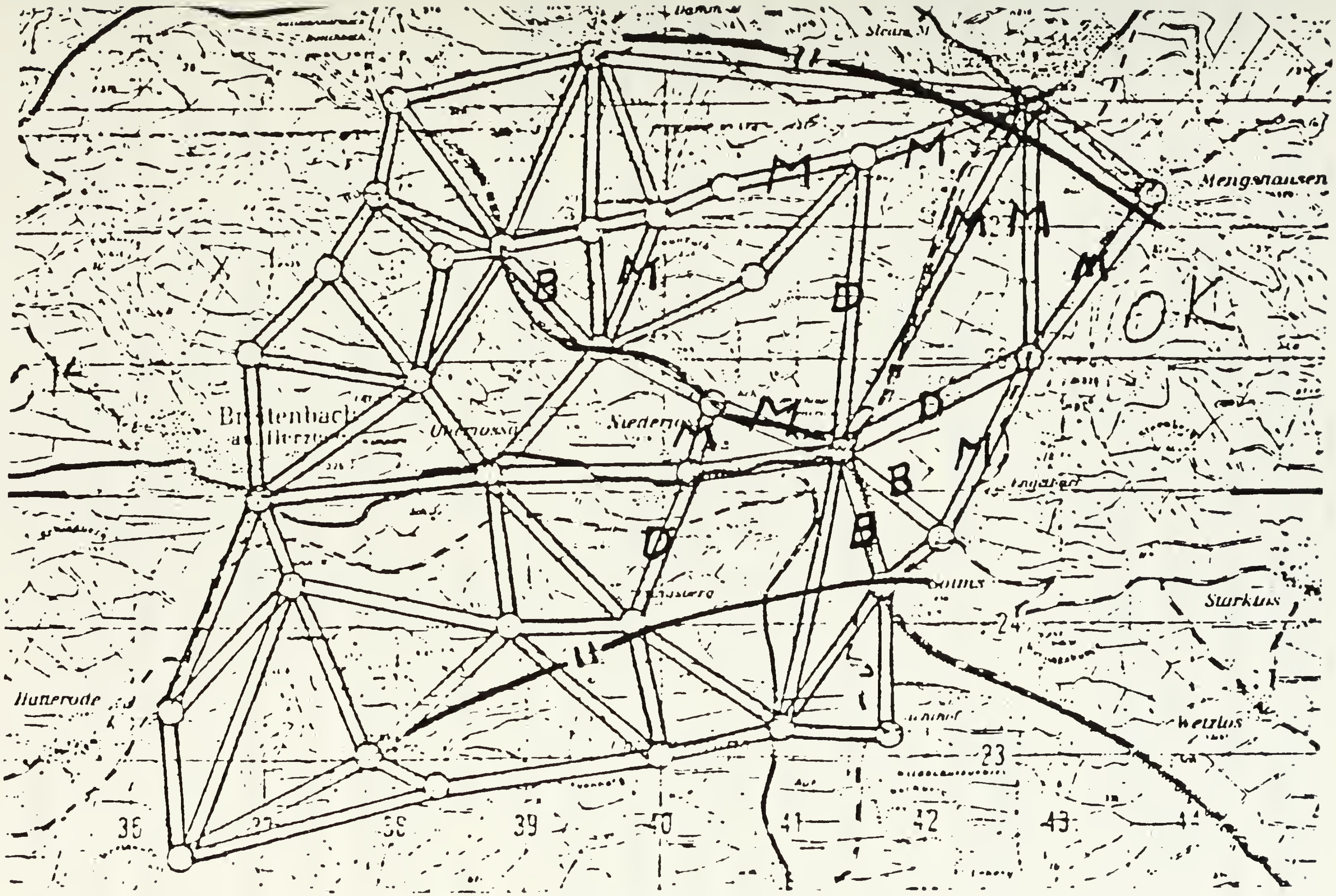

Figure 5.1
Model Obstacle Placement

sequence at most seven times per sector. The Engineer Asset Placement Algorithm requires approximately 75 seconds for a sector with sixteen obstacles to be placed. Again, this time can be greatly reduced when run on a mainframe system, so the scaling up to a corps may not present a severe run time problem.

3. Conclusion

In comparing the algorithm results with the C&CS solution, the only difference is the number of obstacles placed. The reason that obstacles were not placed in the southwest corner of the sector is that the model ran out of assets for more obstacles. This can be attributed to the assets required for the construction of obstacles in the SOP Table. Therefore, slight modifications to this table will correct the problem.

A notable advantage to the network methodology is the ease with which the obstacle plans of higher headquarters and previously placed obstacles can be treated. These obstacles can be assigned as characteristics of the arcs of the network. Therefore, they are overlaid on the sub-network of the battalion in the same manner as terrain features in the battalion's sector. This concept can also be extended to other hierarchical support plans such as artillery fire plans, air support plans, and chemical or nuclear effects.

The results provided by the Engineer Asset Placement Algorithm shows great promise for future uses of the terrain network methodology. With only a few data items to represent the terrain, the algorithm develops sound obstacle plans for a battalion sector. Because of the similarity in the logic of this algorithm and the Unit Placement Algorithm, the resultant plans together represent sound tactical procedures for the use of obstacles to slow the enemy forces to where the unit's weapons systems can have their greatest effect. Another advantage is the level of resolution that can be achieved with this methodology. This model can locate engineer assets placed at the squad level within several hundred meters. It does so efficiently in terms of time and data storage requirements. This could not be achieved by past modeling methodologies.

VI. SUMMARY AND FUTURE DIRECTIONS

A. SUMMARY

This thesis has developed a prototypical model for combat planning using a multidimensional network representation of terrain. It has demonstrated the feasibility of a terrain network methodology for large scale combat modeling.

The model used two rule-based algorithms for the planning of maneuver unit and engineer asset placement. The model was run using a predetermined scenario developed in C&GS literature. The resulting deployment scheme produced by the model closely resembled the solution for deployment proposed by C&GS. The model consistently selected correct avenues of approach through the battalion sector and developed sound tactical plans for defending the sector. With the suggested modifications, these algorithms can be used as planning modules in a production model.

The primary concern of the research was the demonstration of the feasibility of network methodologies for the representation of terrain. In this respect the model produced excellent results. The methodology was capable of representing a large (20 by 70 kilometer) maneuver area with a relatively small data base compared to past methods of terrain representation. The algorithms using this terrain network data base had sufficiently small run times as to make their use in a corps level model feasible. The terrain network methodology was capable of resolving the placement of combat elements down to several hundred meters efficiently. Therefore, this methodology will provide an excellent structure for the terrain representation in the Airland Research Model.

B. FUTURE DIRECTIONS

Several areas of future research are necessary for the incorporation of the two algorithms in an operational model. The boundaries for the battalion sector were treated in the model as inputs. An important feature of the Airland Research Model will be its capability to identify likely avenues of approach and allocate forces to defend these avenues. A vital part of this process is to define the boundaries for lower level units' sectors of responsibility. Research is needed into methods of defining these avenues and boundaries dynamically in the model.

Further research is also needed for methods of aggregating the terrain network. As the level of command changes, the detail of the information needed for planning also changes. The generalized value system will provide for these changes in terms of the value of the different elements of combat in space and time. As yet, it is not clear how the terrain network is to be used to provide the same variable resolution. Several methods have been suggested for the aggregation or collapsing of the network to accomplish these changes in resolution by Manzo [Ref. 12: pp 58-66], but further research is needed in this area.

Most of the work to date has looked at the likely avenues of approach through a sector in terms of shortest paths. As was seen in the Unit Placement Algorithm, it may be necessary to consider the problem from the standpoint of network flows. Network flow formulations are also suggested by Manzo [Ref. 12: pp 69-71] as a means to determine sector boundaries. Further research into the applications of network flow algorithms for the model is necessary.

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